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Procedia Technology 26 (2016) 324 – 332

Procedia Technology

3rd International Conference on System-integrated Intelligence: New Challenges for Product and Production Engineering, SysInt 2016

Function-based feasibility study and benchmark for MID concepts

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Abstract

Molded Interconnect Devices (MID) are three-dimensional structures with integrated electronic circuit traces that facilitate the miniaturization and functional integration of technical products. This opens up new possibilities for the conception and design of products but also comes with specific challenges. The complexity of MIDs has a major influence on the design process of the product and the design of the associated manufacturing system. There are a large number of available MID manufacturing processes composed of various steps, each one with specific advantages and constraints attached to them. As a result, the manufacturing process has to be taken into consideration at an early stage of the product development cycle. A systematic design approach is therefore necessary in order to successfully create a feasible product using MID technology. This paper presents the first part of a procedure that enables a systematic conception of MIDs and the associated manufacturing system while taking product functions into account, starting with a feasibility study for MID concepts.

Peer-review under responsibility of the organizing committee of SysInt 2016

Keywords: Molded interconnect devices; integrative product and production design; function-based development

1. Introduction

Modern technical products are comprised of mechanical, electronic and software components, increasingly shifting the focus of the design process from mechanical engineering towards electrical and software engineering. The resulting products are commonly referred to as mechatronic products or systems, the development of which requires substantial cross-discipline cooperation and coordination in order to be successful [1]. Three categories of mechatronic systems can be distinguished (see Fig. 1). The first category describes the spatial integration of

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Peer-review under responsibility of the organizing committee of SysInt 2016
doi:10.1016/j.protcy.2016.08.042

mechanics and electronics. The key aspect of such systems is the realization of a high functional density in a given installation space. Products from this category are referred to as *integrated mechatronic systems*. The second category comprises multi-body systems with controlled movement behavior. Here, the main focus lies on controlling the movement and behavior of systems through the use of extensive sensory data [2]. The last category encompasses intelligent interconnected systems, focussing on the fusion and interconnection of physical and software systems. Products from this category are referred to as cyber-physical systems [3]. Complex mechatronic systems are often the result of a combination of products from more than one category. Multibody systems, for instance, often include a number of components belonging to the first category, e.g. integrated sensors etc.

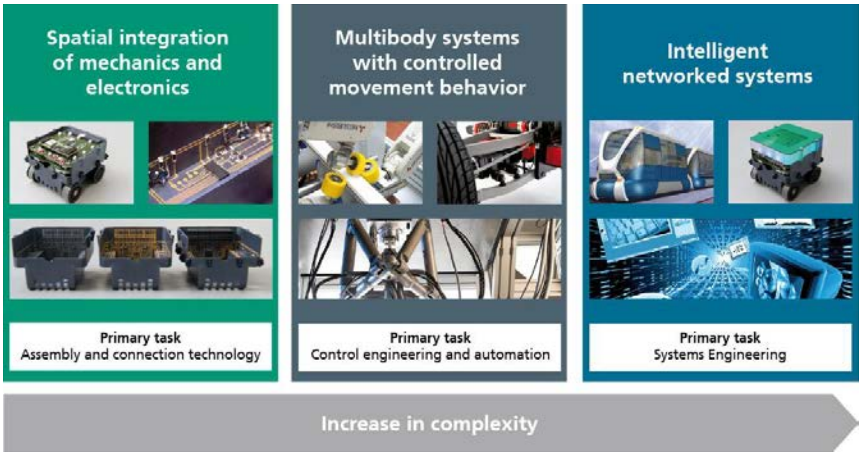

Fig. 1. 3 categories of mechatronic systems [3]

The development of integrated mechatronic systems has to fullfill ever-increasing customer expectations and requirements regarding miniaturization, functional integration, performance and reliability. One way of meeting these requirements and therefore enable the implementation of innovative applications, is the use of Molded Interconnect Devices (MID). MIDs are three-dimensional components with integrated electronic circuit traces that facilitate the miniaturization and functional integration of mechatronic products, for example pressure sensors or integrated antenna structures. This opens up new possibilities for the conception and design of highly integrated and connected products but also comes with a number of additional challenges compared to traditional solutions. The complexity of MIDs has a major influence on the design process of the product as well as on the design of the required manufacturing system. The integral construction, inherent to the MID technology, requires a cross-discipline development approach. Additionally, many different MID manufacturing processes are available, each one with specific advantages and constraints. As a result, the manufacturing process has to be taken into consideration at an early stage of the product development cycle in order to factor in the specific characteristic of the manufacturing process. A systematic design approach is therefore necessary in order to successfully create a feasible product using the MID technology and fully exploit the potential of the technology. This paper introduces an approach that enables a systematic function-based conception of MIDs and the associated manufacturing process. For this purpose, a two-phase approach has been developed that comprises a feasibility study and a subsequent detailed MID development process to guide the user through the process. The individual steps and results for each step of the feasibility study are described in detail in this paper. Furthermore, a software tool is presented that will support this systematic design approach and make it accessible for MID developers.

2. Molded interconnect devices (MID)

Molded Interconnect devices integrate mechanical and electronic functions in a single component. This is achieved by selectively structuring and metallizing a base substrate to create electronic circuit traces on the surface which can then be used to mount and connect SMD components. Additionally, thermal, optical and fluidic functions can be integrated. The MID technology offers high potential with regards to miniaturization, high design flexibility and high functional density [4]. The base substrate for an MID is usually created by injection molding. Generally, any product that combines a spatial base substrate with circuit traces and electronic parts in a single component can be considered an MID. As with most other technical products, MIDs can be manufactured in a number of ways. One aspect that all MIDs have in common is the fact that the manufacturing process is comprised of multiple steps.

2.1. MID manufacturing processes

There are many different manufacturing processes available for the use in MID manufacturing. The most important processes are LPKF Laser Direct Structuring (LDS®) and two-shot injection molding. Futhermore, printing technologies such as Aerosol-Jet have gained more and more attention in the last couple of years. Due to the large number of available manufacturing processes and possible combination of different process steps, it is necessary to subdivide the MID manufacturing process. The MID reference process divides the manufacturing of MIDs into four steps, with each of these steps including the available manufacturing processes (see Fig. 2).

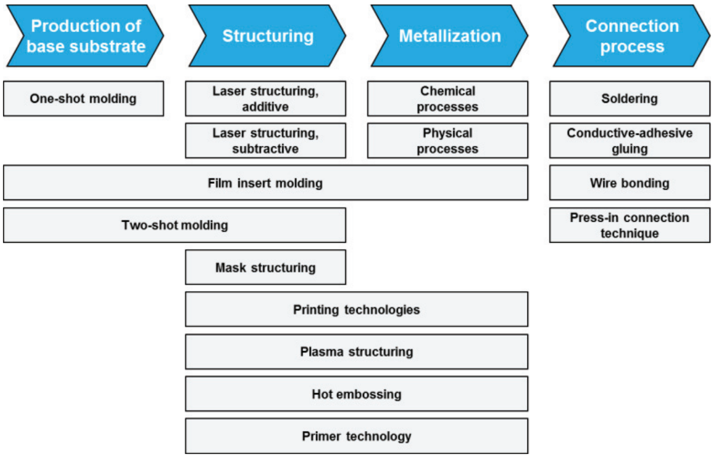

Fig. 2. MID reference process [4, 5, 6]

The first three steps of the MID reference process comprise the manufacturing process for the bare MID. The base substrate acts as the carrier for the circuit traces and the SMD components and can be produced from a wide variety of materials although the most common material is thermoplastic polymer formed in an injection molding process. If the LDS process is to be used for the subsequent step of structuring, a special polymer containing metallic additives has to be used. In the structuring process step, the layout of the circuit traces is structured onto the base substrate. In the LDS process, a laser is used to selectively ablate the surface of a part, thereby exposing the metallic additives. This defines the circuit layout of the MID. In the two shot molding process, two types of polymers are used: One polymer the can be metallized and a second polymer that cannot be metallized. Combining those polymers in two subsequent injection molding steps creates a component that can be partially metallized to create the circuit traces on the surface. After a component has been selectively structured, the circuit traces need to be metallized either chemically or through an electroplating process. Usually, the metallization is done in multiple steps, most commonly applying layers of copper, nickel and a gold finish with several cleaning steps in-between. The last step in manufacturing an MID involves placing SMD components on the base substrate and connecting them to the circuit traces. This can be achieved by soldering, gluing using conductive adhesive, wire bonding or using the press-in connection technique. Depending on the connection process, the solder or glue has to be applied to the connections before adding the electronic components. After that, either the soldering process or the curing of the glue can take place.

2.2. MID applications

The MID technology has been in use for a number of applications, some of which are in large scale series production. The LDS technology, for example, is used for producing antennae for many different communication devices. Half of all smartphones manufactured in 2012, for instance, contained LDS parts [7]. Apart from the freedom of design, another advantage is the high flexibility for changing the layout of the circuit traces, e.g. when adapting the design for different regulatory requirements like frequency bands etc. Another application area of the MID technology is the integration of sensors into structural components. Here, the potential for functional integration and miniaturization is used to produce functional components that optimally utilize the available installation space (e.g. ultra thin OLED-module by OSRAM) [8], arrange SMD components in a specified angle to each other or include mechanical and electronic connectors. Exisiting automotive MID applications show that even demanding requirements can be met (e.g. high margin production, reliability etc.). Examples are a light sensor by HELLA for climate control and a sensor module for adaptive cruise control for trucks by CONTINENTAL [9,10].

3. Challenges for the development of MIDs

The development of MIDs is a complex procedure due to a number of challenges. The cross-discipline nature of developing integrated mechatronic systems applies especially to the MID technology. Mechanical and electronic functions as well as the software need to be developed conjointly. An additional challenge results from the interdependency of an MID product and the manufacturing process as well as the material. Depending on which MID manufacturing process is chosen (e.g. LDS, two-shot molding, etc.), different constraints for the product design such as flexibility requirements, product margins or applicable materials exist. As a result, the manufacturing process has to be designed in parallel with the MID product to ensure compatibility of the product design and the manufacturing processes. Also, the individual manufacturing process steps are largely interdependent. The selected process for manufacturing the base substrate, for instance, has an influence on all of the subsequent manufacturing steps which also needs to be considered during the development. There are specific areas that need to be addressed in order to facilitate an integrative MID development. Aside from technological constraints like reliability, two other obstacles are the lack of a comprehensive systematic development approach that takes feasibility of a concept into account as well as the lack of software tools that support the MID design process [11]. On the one hand, technological aspects are under constant improvement which results in an increase in reliability among other things. The lack of a systematic approach and software tools, on the other hand, have not yet been addressed appropriately. There already exist some MID development approaches but none of them factor in the evaluation of a new concept regarding the MID technology. The approach for a product optimization by PEITZ [12], for instance, can only be applied to existing electronic products and does therefore not work for entirely new concepts. These can, however, be used as a reference for the development of the presented approach.There has also been some ongoing development on MCAD and ECAD integration for MID with projects like NEXTRA® [13] and MIDCAD [14]. These tools can support the physical design phase but do not offer any support for the developer during the conception phase or assist with the design of the manufacturing process. In fact, there is no step-by-step guideline which suggests optimal design possiblitites to the developer or which assists them during the decision process e.g. indicating whether a concept can be implemented as an MID application or if further changes are required. Moreover, there are no tools that support the developer in the creative design process, for instance, by offering solution patterns to known problems.

Another obstacle for most developers is the lack of access to information regarding the MID technology. Due to the large number of different manufacturing processes, most companies that are part of the MID value chain only focus on specific processes. Because of their specialization, they have a lot of expertise on their manufacturing processes, which can not necessarily be applied to other processes. As a result, interaction with a specific manufacturer might result in defining the manufacturing process chain early in the development process regardless of the advantages that other manufacturing processes might have for a specific product concept. Assessing the feasibility of an MID product concept without taking all the available manufacturing processes and their respective advantages and constraints into account, decreases the chances of developing an optimal product. Besides, not knowing the interdepencies within the several steps of the MID process chain could be a serious issue during the ongoing development and manufacturing process because of distributed responsibilites. The coordination of all partners demands an overview on all constraints and cause and effect relationships. The MIDIS database, developed at the FAPS - Institute for Factory Automation and Production Systems, contains essential information on MID applications, manufacturing processes and materials [15]. It offers general information but no development-specific support.

4. Methodology for function-based development of MIDs

The need for a systematic approach becomes evident when considering the myriad possibilities and constraints that a developer has to consider when developing an MID product. The lack of easily accessible information often results in only incomplete knowledge on MIDs which in turn hinders the design of an optimal product. These aspects are addressed in our research which aims at creating a systematic approach for the early phase of the MID development with a focus on the evaluation of the feasibility of a concept, supporting the decision-making process as well as aggregating and centralizing all necessary information essential for a holistic development approach. The overall goal of the project is to implement the development design approach including all the necessary information in a web-based software tool. Through interviews with industry experts, two categories of MID development projects were identified. The first category encompasses projects that require a feasibility study, where a client has a product concept that they would like to realize using the MID technology. They do, however, lack the required know-how and experience in MID-specific design (e.g. they often aim at substituting an existing PCB, thereby failing to exploit the potential offered by the MID technology). As a result, the product feasibility needs to be assessed and the product concept has to be heavily modified in most cases, which requires close and time-consuming collaboration with the client. This issue could be remedied by supplying the first-time MID designer with essential information on the MID technology and systematically guiding them through a feasibility assessment at an early stage even before the overall system architecture is determined or peripheral moduls are fixed by a design freeze. The second category describes detailed development projects. Those projects usually start with a concrete design that the client wants to bring to production. In this case, the client is already experienced in the design and manufacturing of MIDs. Nevertheless, there is a need for consultation especially regarding product requirements, product functions and the constraints resulting from the possible manufacturing process chains as well as target costs. This process could be supported by providing methods for analyzing MID-relevant aspects of product concepts, matching required functions with possible solutions and comparing the costs of different process chains enabling a cost-benefit consideration.

We have developed a methodology for a systematic MID development that addresses both types of projects and is therefore split into two phases. Fig. 3 shows the first part of a procedure model that covers the feasibility study as part of the overall approach. This paper focusses on this first phase. It addresses the need for an MID-specific feasibility assessment and can be broken down into three steps: Product concept description, data analysis and benchmark, and evaluation of results. Each of the steps employs methods that enable a systematic execution of the individual tasks leading to the results shown on the right side of the procedure model. Subsequently, all phases are explained in detail.

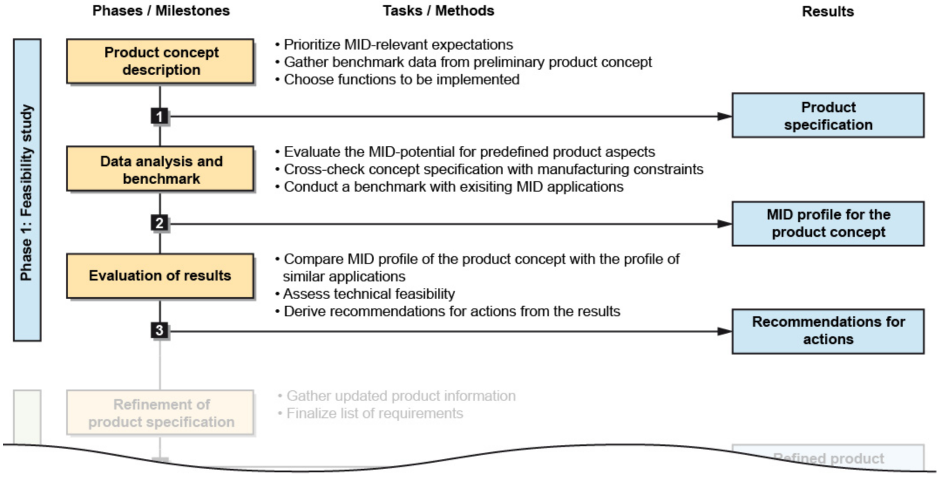

Fig. 3. First phase of the procedure model covering the feasibility of MIDs

Product concept description

The first step of the feasibility study serves as a preparation for the subsequent steps. Relevant information on the product concept has to be collected including preliminary requirements, functions as well as the priorities of employing the MID technology (e.g. flexibility for changing the circuit layout, miniaturization, functional integration etc.). In order to specify which information is necessary at this early stage of product development, the minimum criteria was identified in the course of multiple workshops and interviews with industry experts. These criteria were categorized into attributes and characteristics for each attributes were defined. Possible attributes are geometry of the product, number and orientation of functional surfaces, operating temperature, and position of the circuit traces among others. By going through the attributes and determining their characteristics, the product concept can be specified. Furthermore, based on an expanded MID function catalog, subdivided into electronic and mechanical functions [4], the functions to be implemented for the concept can be selected. Additionally, the MID-specific advantages need to be prioritized to specify the focus of the development project.

Data analysis and benchmark

In the second step of the feasibility study, the input from the first step is used to create a profile for the application concept. This profile combines the MID potential, product feasibility and information on similar products. **Fehler! Verweisquelle konnte nicht gefunden werden.** illustrates the process of the analysis and benchmark process.

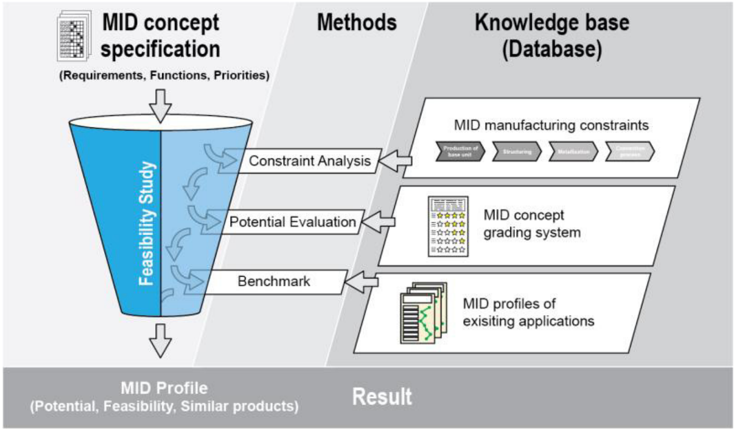

Fig. 4. MID feasibility study

A number of methods are incorporated into the process to create the MID profile. Initially, a constraint analysis is conducted, taking the attributes of the product concept into account and cross-checking them with known MID manufacturing constraints. This ensures that none of the MID attributes conflict with the minimum constraints that result from taking all available MID manufacturing processes into account. The result is an overview of the applicable manufacturing processes and materials for the current form of the concept. The MID-specific potential is then evaluated using a grading system developed on the basis of approaches by EHRLENSPIEL and LINDEMANN [16, 17]. The grading sysem was created in conjunction with industry experts from various companies in the MID process chain as well as by analyzing existing applications. The attributes of the concept are graded using a scale from 0-4, where 0 represents no potential and 4 represents high MID-relevant potential. The prioritization from the first step is used to generate a weighted assessment. This ensures that low-potential features, that do not contribute substantially to the application-specific goal, do not lower the overall potential disproportionally. An example is a component with high functional integration where miniaturization is not a priority. The weighed assessment could still confirm that the concept has a high MID-specific potential even if size is of little concern.

As stated above, MID applications have been graded during the preliminary work using the presented approach. These results can be used for a benchmark that compares the new concept with all existing applications. In order to identify the most relevant applications, products with similar functions as the product concept are selected for further evaluation (See Fig. 5). The results support the creative design process by presenting the developer new ideas and solutions that have been successfully brought to market. This function-based solution process is sutaible to disrupt the conventional module-oriented approach, typically characterized by a seperation of different development disciplines. Therefore, the benchmark shows design possibilities and suggests practical examples to the developer.

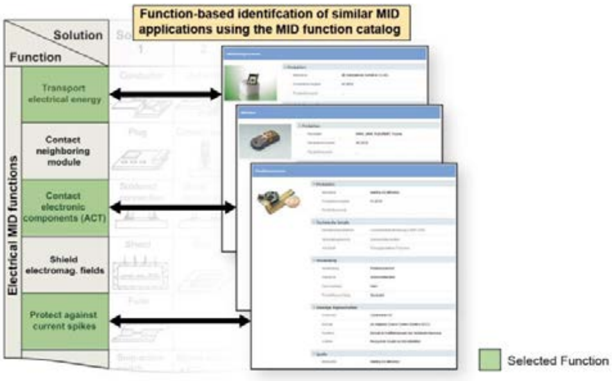

Fig. 5. Identification of similar applications using the MID function catalog

Evaluation of results

The MID profile for the concept is used as the basis for developing recommendations for action. Similar MID applications can be used as references and help generate additional ideas. The results of the weighted assessment are used for identifying weaknesses of the concept with regard to MID-specific advantages. The feasibility study helps in refining the product concept, creating the foundation for the subsequent development process.

Tool support

Both phases will be implemented in a web-based tool that assists developers during each step of the development process. The aim of the tool is to provide access to aggregated and curated information on MID for use in the evaluation of a product concept. The tool will be linked to the MIDIS database to ensure that the latest information (e.g. MID applications, manufacturing processes, materials etc.) can be taken into account. The tool will be based on its own database that is linked to the MIDS database. This is done to ensure that the information from MIDIS can still be accessed and updated separately from the tool-specifc database. Furthermore, the new database will contain additional information necessary for the individual steps of the feasibility study and subsequent design process (e.g. compatibility of manufacturing process steps).Fig. 6 shows a schematic of the tool and the relation between the databases and the relevant algorithms.

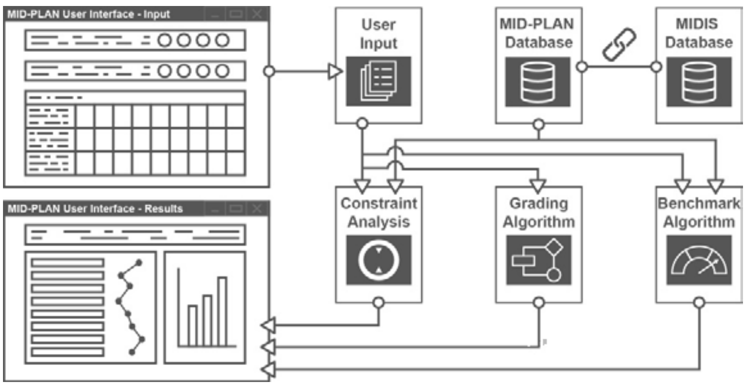

Fig. 6. Functionality of the MID-Plan tool for the feasibility study

For the feasibility study, the user will enter the necessary information through a web interface that guides them through the process step by step. As part of the feasibility study, the tool conducts a constraint analysis by checking the compatibility of the input data with the known constraints of all MID manufacturing processes. A grading algorithm determines the unweighted and weighted assessment of the concept. The benchmark algorithm will identify applications similar to the product concept based on the functions selected for the concept and generate a comparison of the current concept and the profiles of selected applications.

5. Conclusion

The MID technology offers great potential with regard to miniaturization, functional integration, and design flexibility. There is, however, a lack of a systematic development approach as well as a lack in software tools that can support the development and creative design process. To address these issues, a systematic design approach has been developed as part of our research. A two-phase process model has been created to illustrate the design approach. The first phase is an MID feasibility study that enables the evaluation of a concept, taking functions, priorities and preliminary requirements into account. This phase and the underlying methods were described in detail in this paper. Also, the concept for a tool that will implement the design approach has been presented. Future work will focus on the second phase of the design approach covering the function-based development of an MID and the manufacturing system. Furthermore, the web-tool containing all necessary information for the MID development will be developed and evaluated.

Acknowledgements

Parts of this research and development work were carried out within the IGF research project 18445 N. The project has been funded by the AiF within the program for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy (BMWi) based on an enactment of the German Parliament. The authors would like to thank the project committee for their advice. The authors are responsible for the contents of this publication.

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